Federal Motor Vehicle Safety Standards are based on extensive testing and analysis. The background research for these standards is available to guide the design of safety belt systems for wheelchair occupants. This report examines specifications for the shoulder belt geometry for occupants of wheelchairs in public and private transportation vehicles. The report first reviews the research and the test data used to develop federal safety standards for restraint systems, then applies current research and modeling to extrapolate the results to wheelchair occupants. Preliminary modeling to assess the influence of shoulder belt anchor point location on wheelchair-occupant crash dynamics indicates that anchor point location should be selected with care since occupant and wheelchair crash dynamics are affected.
INTRODUCTION

Federal Motor Vehicle Safety Standards are based on extensive testing and analysis. The background research for these standards is available to guide the design of safety belt systems for wheelchair occupants. However, in public transportation the vehicle geometry permits a much wider latitude in the design and configuration of the safety belt systems than in passenger cars.

This project examines specifications for the shoulder belt geometry for occupants of wheelchairs in public and private transportation vehicles. This report first reviews the research and the test data used to develop federal safety standards for restraint systems, then applies current research and modeling to extrapolate the results to wheelchair occupants.

APPLICABLE STANDARDS

The specification of the upper anchorage location for the shoulder belt is included in Federal Motor Vehicle Safety Standard (FMVSS) 210, "Seat Belt Assembly Anchorages." This standard permits a range of locations above and aft of the shoulder reference point. The permissible range is shown in Figure 1. The width distance relative to the seat centerline is not specified. In most passenger cars, the distance from the seat centerline to the anchorage location is in the range of 7 to 10 inches. For wheelchair occupants, distances from the centerline of at least 10 inches are generally needed to accommodate the half width of the wheelchair. For public transit systems, a distance from the seating centerline to the side wall of 24 inches in not unlikely. Further, the lower roof of passenger vehicles limits the practical upward excursion of the anchorage point more than it does in public transit vehicles. These differences amplify the need for additional guidance in the placement of the shoulder belt anchor for wheelchair occupants.

The wide latitude of anchor locations allowed by FMVSS 210 permits some belt configurations which are uncomfortable and do not provide optimum crash protection. The problem of motor vehicle safety belt discomfort was recognized in the Intermodal Surface Transportation Efficiency Act of 1991. That Act required the Department of Transportation to address the problem of safety belt comfort. In May 1992, the National Highway Transportation Safety Administration (NHTSA) published an Advanced Notice of Proposed Rulemaking to improve the design of safety belts. In 1992, the Canadian Ministry of Transportation published their proposal to improve belt safety. Finally, in April 1994, NHTSA published a Notice of Proposed Rulemaking which is intended to improve safety belt comfort. The research in support of these regulatory initiatives provides the basis for recommendations for shoulder belt configurations for wheelchair occupants.

RESEARCH AND RULEMAKING ON BELT FIT

Research conducted in the early 70’s by Man Factors Inc. recommended guidelines for the geometry of safety belts to insure a “good” fit [1]. The research was based on tests of 37 subjects. With each subject tested, the belt geometry was changed until it was decided the best fit was obtained. According to the report, “Such a geometry resulted when the harness crossed the shoulder midway between the neck and acromium, passing over the sternum midway between the nipples and making the junction with the belt at the inboard pelvic crest.” The proposed geometry which represented the compromise for the best fit is shown in Figure 2.

The Man Factors Inc. research was updated in 1978 [2]. In this project, 62 test subjects evaluated 5 different passive belt systems, using procedures similar to the earlier study. The result of the study was a “belt fit” envelope marked on the chest of a 50% male dummy, as shown in Figure 3. The resulting envelope was intended to provide proper fit to 90 percent of the population (5% female through 95% male.)

A third study was completed by Man Factors in 1980 [3]. The objective of this study was to further develop the envelope and to avoid placing unnecessary constraints on the belt geometry. It was found that both males and females could tolerate belts which were 0.5 inches closer to the neck, and 0.5 inches closer to the shoulder. As a consequence, a new trapezoidal envelope was drawn as shown in Figure 4. The shoulder anchorage point which produced the belt configuration at the centerline of the comfort zone was as follows: \( x = 10.75 \) inches, \( y = 8.5 \) inches, \( z = 28 \) inches. The coordinate system was defined as \( x \) being positive in the direction of travel (forward), \( y \) being positive to the right of the occupant, and \( z \) being positive in the upward direction.

NHTSA proposed that the belt anchorage should permit the belt to cross the centerline of the chest of the 50% male dummy at about 16” above the seat.
The recommended belt angle at the chest centerline is 55 degrees relative to the horizontal plane. This geometry, as shown in Figure 4, provided suitable comfort and protection.

Further analysis of the research by NHTSA staff resulted in the development of two envelopes - one on the front of the chest and a second on the shoulder. The resulting zones, shown in Figure 5, were published in an Advanced Notice of Proposed Rulemaking [5] (see Appendix A). This configuration was less restrictive, but at the expense of some discomfort for the population larger than the 90% male and smaller than the 10% female.

NHTSA found that it was necessary to adjust the comfort zone to permit optimum fit for different size occupants. Table I shows the recommended adjustments in the Sternum Reference and Shoulder Target for other sizes of dummies. These dummies are representative of a 6 year old child, a small female, and a large male. In the event a belt installation is for children or small adults, the Sternum Reference and Shoulder Target Zones should be adjusted accordingly. When the occupant is seated in the normal seating position (seat in mid-range position), the belt anchors or guides should allow the shoulder belt to pass completely within the target zones to assure a proper fit.

After reviewing comments on the 1992 Notice, NHTSA published their response in a Notice of Proposed Rulemaking in April 1994 [6] (see Appendix B). The 1994 proposal is to improve shoulder belt fit by requiring that the shoulder belt anchorage be adjustable. At least 5 centimeters of shoulder anchorage adjustment would be required in all vehicles by September 1, 1996. The adjustable anchorage provides the opportunity for even better fit than the fixed point anchorage, which satisfies the geometric requirements specified in Figures 4 and 5.

The Canadian Ministry of Transport also proposed a belt fit standard in 1992. The proposed standard employed a Belt-fit Test Device which is described in Appendix C.

These proposals recognize that belt comfort is related to crash safety. Comfortable belts are more likely to be worn and worn correctly. Further, crash tests show that belts which are positioned for comfort also provide good crash protection. Although the comfort zone envelopes are not currently required by federal standards, the research provides valuable guidance in positioning shoulder belts for comfort. Consequently, the results also can be used to guide the placement of shoulder belts for wheelchair occupants.

**RESEARCH IN BELT PERFORMANCE FOR VARIOUS ANCHOR LOCATIONS**

Occupant kinematics in a crash are influenced by the placement of the shoulder belt. If the belt is too high and rides close to the neck, unfavorable head accelerations and neck loading result. If the belt is too low, inadequate support to the chest is provided and excessive abdominal loading and head excursion result. In general, research has shown that belts which fit well perform well in crash tests.

A series of 29 frontal impacts and 18 oblique (thirty degree) frontal impacts with a crash severity of 30 mph were conducted on a test sled to determine belt performance in the comfort zone [7]. The test configuration was a 1981 2-door Chevrolet Citation. Tests were conducted with the belt at the inboard edge, the outboard edge and the centerline of the comfort zone using 5%, 50% and 95% dummies. The results showed that placement within the comfort zone provided satisfactory performance on all dummies.

Tests of a passive (two point) shoulder belt configuration similar to the VW Rabbit were conducted by Calspan [8]. The test program consisted of 40 sled tests with both driver and passenger dummies subjected to frontal, 30 degree oblique, and 90 degree lateral impacts. Tests evaluated four basic belt positions and three sizes of dummies. The range of anchor locations included baseline, ± 6 inches vertically and ± 8 inches horizontally.

Selected test results to illustrate the influence of height adjustment are shown in Table II. These results are for a 50% male dummy in a 30 MPH, zero degree frontal crash. The dummy was seated on the passenger side of a test buck in which the baseline configuration was close to the geometry of a 1976 2-door VW Rabbit.

A review of the test films show that for the higher mounted anchor, there is a considerable amount of head whipping, resulting in the increase in head acceleration (G’s) and Head Injury Criteria (HIC). Tests of the fifth percentile female dummy with the higher mounted anchorage produced extreme neck flexion, with head G’s above 100, and HIC above 1000. For the lower mounted anchor, the belt rides beneath the dummy’s ribs, and the head strikes the dashboard. These general kinematics have also been noted by other...
authors who examined the performance of manual three-point belts [9].

In the 30 degree oblique tests, the higher anchorage location induced unfavorable rebound motion. The 50% and 95% percentile dummies both produced head strikes on the B-pillar. However, the authors note that this response may be partially due to the dummy design which retains the belt on the shoulder. On a human, the belt would be more likely to slip off, resulting in increased head excursion and decreased rebound.

The relationship between belt horizontal location and dummy response for the 50% dummy are shown in Table III. The belt anchorage in the 8 inch forward position was reported to be close to the geometry in the 4 door Rabbit. The baseline position was close to the geometry in the 2-door VW Rabbit.

A review of the data in Table III shows that the head excursion increases as the belt location moves forward. Table II data shows that head excursion increases as anchorage moves down. The consequence of increased head excursion is increased opportunity for the head to contact vehicle components in front of the seated occupant. The data summarized is for the passenger dummy. Consequently, no steering wheel was present. For the driver dummy, the head strikes the steering wheel and the HIC values generally increase for the same conditions which produce increased head excursion for the passenger dummy.

The chest acceleration data shows a decrease as the anchorage moves forward. However, a review of films shows that the belt underrides the ribs and penetrates the abdomen - an undesirable result which can induce abdominal injuries.

The relationship between the upper anchorage vertical position and the belt location on the chest relative to the ATD sternum reference point is shown in Figure 6. The top curves are for three sizes of dummies with the seat in the center location. The lower curves are for the seat adjusted full forward for the 5%, midway for the 50% and full aft for the 95%. The belt angle positions relative to the comfort zone are shown in Figure 7. It is evident from the figure that the configuration lies outside the best angle for comfort.

The relationship between the upper anchorage horizontal position and ATD sternum reference point are shown in Figure 8. The data shows that moving the belt to the full aft position brings the belt angle into the comfort range.

Side impact tests conducted at 13.7 mph showed that belt placement within the range of the comfort zone had no observable influence in the side impact kinematics.

APPLICABILITY OF RESULTS TO WHEELCHAIR OCCUPANTS

The belt comfort geometry defined by Figures 4 and 5 offer guidance for shoulder belt anchorage locations for wheelchair occupants. The same geometry can be applied, but with the ATD sternum reference point measured from the wheelchair seat plane. Man Factors Inc. research located a baseline anchorage for shoulder belt comfort at $x = 10.75$ inches aft (measured from the dummy H point); $y = 8.5$ inches (measured from the centerline of the dummy); $z = 28$ inches up (measured from the seat plane) [3].

To maintain the 55 degree comfort angle the anchor point should be moved upward as it is moved outward beyond 8.5 inches. The tangent of the 55 degree angle defines the upward to sideways movement ratio of 1.42:1. The resulting configuration is shown in Figure 9a.

Variations in aft anchor position have not been defined from the comfort research reported in the references. However, to maintain the geometric relationship in the x-z plane of the belt angle relative to the shoulder, the anchor needs to be moved rearward as the belt is moved upward. The ratio of rearward movement to upward movement suggested by preliminary modeling is 1.5:1. The resulting configuration is shown in Figures 9b and 9c.

For comparison, the belt configurations permitted under the Australian Wheelchair Standard are shown in Figure 10.

WHEELCHAIR TESTING AND MODELING

Testing sponsored by the Cleveland Clinic conducted preliminary evaluation of dummy performance in a wheelchair [10]. The test configuration attempted to maintain reasonable belt geometry, but moved the anchorages laterally to a distance of 24 inches relative to the centerline of the seat. Some of these tests produced head G’s in the z-direction which approach or exceed 70 G’s. A head acceleration of 70 G’s in the z-direction is the maximum permitted under a proposed safety standard.
To further explore the occupant kinematics with varying anchorage location, a computer model was employed. The ATB/CVS occupant model was used to simulate frontal crashes of the Hybrid III dummy seated in wheeled mobility devices. The ATB/CVS model was developed by the U.S. government [11]. The Hybrid III dummy data was based on measurements made by the U.S. Air Force [12,13] and sled validation conducted under government grant from the Centers for Disease Control [14]. The validation of the dummy model in the wheelchair which is being proposed for use in ISO Standard 10542 “Wheelchairs—Tie down and occupant restraint systems for motor vehicles” was also conducted under a U.S. government grant [15,16]. The documentation for the model, and instructions for its use are contained in a University of Pittsburgh Report [17].

Preliminary results of selected simulations are summarized in Table IV. These preliminary results show that the configuration shown in Figure 5 provides good dummy kinematics in the zero degree frontal barrier crash at a severity of 30 mph. The simulations use as a baseline the ISO wheelchair which has been tested in five different laboratories under identical test conditions. For the laboratory test conditions, the slack in the shoulder belt was set at 0.5 inches. The upper anchorage point was approximately 9 inches outboard of the center of the seat, 9 inches rear of the shoulder reference point and 48 inches above the floor. In this configuration, the belt angle is 53 degrees, and the belt height is 2 inches above the reference point defined by Zeigler [4]. Simulation 9Y-48Z (with 0.5 inches of slack) produces results which are very close to the test results. A second simulation was made to evaluate the consequence of increasing the slack to 2.5 inches. The results show an increase in the head acceleration in the z-direction and the forward displacement.

Run 24Y-48Z shows the result of moving the anchor outward to 24 inches from the seat centerline. The result changes the belt geometry so that the angle in the frontal plane is about 30 degrees and the result is generally similar to the test case in Table II in which the anchor was moved down 6 inches. For this case, the head excursion increases significantly and the body moves sharply to the right on rebound. The head acceleration in the z-direction also increases, particularly when slack is introduced.

The initial four simulations show that belt slack has a large influence on head G's and neck loading, for both favorable and unfavorable belt geometries.

Run 2Y-5Z examines the consequence of raising the belt anchor to 60 inches above the floor. The belt angle in the frontal plane is 43 degrees. High head acceleration in the z-direction is produced and the dummy rebound is to the left.

Run 2Y-6Z shows the results of moving the anchor 12” higher. The belt angle in the frontal plane improves to 50 degrees in this configuration. High head accelerations in the z-direction and head excursions result. However, the rebound kinematics are improved and the dummy moves only 5.8 inches to the left after 140 ms of rebound. Run 2Y-6Z-1X is similar to 2Y-6Z, but the anchor is moved rearward by 12 inches. Head G's and head excursion are reduced.

To assess the performance of the belt system when the shoulder belt anchor is located in accordance with the geometry recommended by the NHTSA’s research, two additional configurations were modeled. The results are reported in Table V.

For the “base” configuration, the anchor is located in the position used in the Man Factors research program as the baseline location [3]. The “extended” configuration locates the shoulder belt anchorage two feet rearward, but moves the anchor along the location line shown in Figures 9a,b and c so that the same belt geometry on the dummy is maintained. The results show that the head excursion increases as a consequence of the longer belt. However, the occupant kinematics are maintained for the frontal crash mode.

Overall, the modeling confirms that maintenance of the recommended belt geometry is important. There is a need to move the anchor point rearward as it is moved upward and outward to prevent excessive head excursion and neck loading. Additional testing is needed to establish the best configurations. Additional analysis of shoulder belt anchorage point location and its effects on occupant kinematics are contained in a University of Pittsburgh technical report [18].

SUMMARY AND CONCLUSIONS

This study reviews the existing regulations and research associated with the fit and protection afforded by a shoulder belt worn by the able-bodied passenger or driver. Research indicates that a shoulder belt which fits the occupant such that comfort is maintained, generally provides the best occupant protection. This concept has been demonstrated by the NHTSA proposed comfort zone in Figure 5, which can also be applied to wheelchair users during transportation. Since large variation of the anchor position in the fore
and aft (x) direction may occur due to physical vehicle constraints, such as windows, it is imperative that the belt geometry in the x-z (or sagittal) plane be maintained as the anchor is moved beyond the baseline scenario established by Man Factors. That is, as the anchor point is moved upward it should simultaneously be moved rearward, establishing a shallow angle as it passes over the shoulder in the x-z plane. Similarly, belt geometry in the frontal (y-z) plane should be maintained by moving the anchor point upward as it is moved outward beyond the Man Factors baseline of y=8.5”.

Preliminary modeling to assess the influence of the location of the shoulder belt anchor point on wheelchair-occupant crash dynamics indicates that anchor point location should be selected with care since the crash dynamics are in fact affected. Placement of the shoulder belt to an anchor point within the NHTSA prescribed comfort zone to maintain belt geometry should be established as a goal. Simulations of wheelchair transportation crashes yield the most desirable occupant dynamics when the belt complies with this goal. Furthermore, in all anchor point scenarios, introducing shoulder belt slack increases both head acceleration and excursion in the forward, x, direction.

REFERENCES


15. NIDRR 1991, Grant Nr H133E00006, “Rehabilitation Center in Engineering for Personal Licensed Transportation for Disabled Persons”, awarded to University of Virginia, July 1, 1991.


Figure 1. Location of Anchorage for Upper Torso Restraint
Figure 2. Baseline Belt Anchorage Configuration
Man Factors Research Program (DOT HS-805 594)
Upper belt anchor or D-ring departure points should be above dummy's shoulder whenever the webbing crosses the shoulder (i.e., so that the webbing departs aft at a positive angle).

* Compliance envelope, i.e., torso belt (standard 2") falls within this area when deployed.

Figure 3. Compliance Envelope for a Proper Fitting Seat Belt
(DOT HS-805 597, pg.A-2)
Figure 4. Modified, Wedge-Shaped Envelope
(DOT HS-805 597, pg.29)
Figure 5. ANPRM Proposed Belt Comfort Zone
### TABLE I. SCALED MEASUREMENTS FOR COMFORT ZONE

<table>
<thead>
<tr>
<th></th>
<th>Sitting Height (in.)</th>
<th>% of 50th Male</th>
<th>N1 (in.)</th>
<th>N2 (in.)</th>
<th>Sternum Reference (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 yr old</td>
<td>25.4</td>
<td>71</td>
<td>2.0</td>
<td>3.6</td>
<td>10.75</td>
</tr>
<tr>
<td>5th female</td>
<td>30.9</td>
<td>87</td>
<td>2.6</td>
<td>4.3</td>
<td>13.9</td>
</tr>
<tr>
<td>50th male</td>
<td>35.7</td>
<td>100</td>
<td>3.0</td>
<td>5.0</td>
<td>16.0</td>
</tr>
<tr>
<td>95th male</td>
<td>38.0</td>
<td>106</td>
<td>3.2</td>
<td>5.3</td>
<td>17.0</td>
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</tbody>
</table>

* Measurements for the 50th percentile male were specified in the ANPRM

### TABLE II. TEST RESULTS FOR VARYING SHOULDER BELT ANCHOR HEIGHTS

<table>
<thead>
<tr>
<th>Belt Anchor</th>
<th>Head G</th>
<th>HIC</th>
<th>Head Excursion (in.)</th>
<th>Chest G</th>
</tr>
</thead>
<tbody>
<tr>
<td>UP 6&quot;</td>
<td>61</td>
<td>541</td>
<td>19.5</td>
<td>40</td>
</tr>
<tr>
<td>NORMAL</td>
<td>36</td>
<td>208</td>
<td>23.2</td>
<td>34</td>
</tr>
<tr>
<td>DOWN 6&quot;</td>
<td>74</td>
<td>667</td>
<td>34.2</td>
<td>39</td>
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</table>

### TABLE III. TEST RESULTS FOR VARYING HORIZONTAL ANCHOR LOCATION

<table>
<thead>
<tr>
<th>Belt Anchor</th>
<th>Head G</th>
<th>HIC</th>
<th>Head Excursion (in.)</th>
<th>Chest G</th>
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</thead>
<tbody>
<tr>
<td>AFT 8&quot;</td>
<td>54</td>
<td>590</td>
<td>17.7</td>
<td>41</td>
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<tr>
<td>AFT 4&quot;</td>
<td>54</td>
<td>598</td>
<td>19.3</td>
<td>48</td>
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<tr>
<td>NORMAL</td>
<td>36</td>
<td>208</td>
<td>23.2</td>
<td>34</td>
</tr>
<tr>
<td>FWD 4&quot;</td>
<td>50</td>
<td>505</td>
<td>24.2</td>
<td>34</td>
</tr>
<tr>
<td>FWD 8&quot;</td>
<td>48</td>
<td>489</td>
<td>27.7</td>
<td>27</td>
</tr>
</tbody>
</table>
Figure 6. Effect of Belt Anchor Vertical Location on Belt Geometry
Figure 7. Belt Position and Angle Compared to Comfort Zone Requirements
Figure 8. Effect of Belt Anchor Longitudinal Location on Belt Geometry
Figure 9a. Desired Shoulder Belt Angle in Frontal Plane

Figure 9b. Desired Shoulder Belt Angle in Sagittal Plane
Figure 9c. Desired Shoulder Belt Angle in Horizontal Plane
Figure 10. Anchorage Location Specified by Australian Standard

Note: Shading indicates permitted zones on either side of the seating reference plane.

25 + 285 = A
55 + 75 = B
APPENDIX A

ADVANCED NOTICE OF PROPOSED RULEMAKING
NHTSA 1992
APPENDIX B

NOTICE OF PROPOSED RULEMAKING
NHTSA 1994
APPENDIX C

REQUIREMENTS FOR SAFETY BELT FIT
PROPOSED IN CANADA
Technical Report #1

FITTING MOTOR VEHICLES SHOULDER BELTS TO WHEELCHAIR OCCUPANTS

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July, 1994